Renewable and Sustainable Energy Reviews 37 (2014) 469–479

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# Technological capabilities for innovation activities across Europe: Evidence from wind, solar and bioenergy technologies

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ARTICLE INFO

*Article history:*
Received 22 December 2013
Received in revised form
9 April 2014
Accepted 27 April 2014
Available online 4 June 2014

*Keywords:*
Technological capabilities
Composite indicator
Innovation patterns
Renewable energy technologies

ABSTRACT

This paper contributes to the development of renewable energy innovation metrics through an exploration of innovation patterns across the European countries in 2010. The identified localized innovation capabilities describe the health of the wind, solar and bioenergy sectors, highlighting a concentrated RES innovation activity within four countries: Germany, France, United Kingdom and Denmark. The association of technological capabilities along the innovation composite indicators allows the extraction of useful insights of the role of environmental policies on employment and technological change. Briefly, the corporate research investment per patent is lower for wind energy (EUR 0.61 million) and higher for PV and biofuels (approximately EUR 1 million). Important lever of innovation capabilities across Europe is identified within public support to deployment, which provides significant insights in terms of economic efficiency of generation technologies; the investigation finds job ratios which are higher for wind and lower for PV technology. As the evolution of the market drives the patterns of innovation activities for all selected technologies, considerable financial consequences are identified in the context of delocalization of clean technology manufacturers.



**Contents**



## 1. Introduction

In the field of renewable energy sources (RES), innovation activities are seen as one of the key drivers in fulfilling the 20/20/20 climate and energy targets in Europe [1]. In 2010, considerable research investments (EUR 5.13 billion) have supported the development of low carbon technologies, 86% of which were in support of three technologies: wind energy, solar energy and bioenergy [2]. Although, across European countries in 2010, EUR 1 billion of public funding supported research and demonstration activities in wind, solar and bioenergy technologies, in relative terms, this investment remains low (0.03% of GDP) compared to the 20/20/20 targets (research accounting for

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http://dx.doi.org/10.1016/j.rser.2014.04.067
1364-0321/

approximately 3% of GDP). An efficient policy design that is able to enhance the synergies and research efforts in low carbon research and technology development could also accelerate the integration of these technologies into the national energy mix.

The choice of the innovation indicators for low carbon energy technologies carries a significant importance for policy making. Two main approaches are used in measuring the intensity of innovation activities: the econometric and the composite indicators approach [3,4,5]. The econometric approach relies extensively on the framework of the standard endogenous growth literature [6] that considers the growth fostered by innovation, which uses knowledge produced by research activities [7,8]. In addition, the innovation activities are induced by environmental policies that seek to change the opportunity costs associated with the use of environmental resources [9,10]. The strand of the literature focusing on the composite innovation indicators seeks to provide a larger picture than the one of extracting information from each of the individual indicators (*i.e.*, the patents). Rather than a mere association between *a specific policy* and *the innovation level*, the aim of these studies is to create an indicator capable of measuring the aggregated innovative capabilities of different countries in the field of energy technologies. Related studies used factorial analysis [11,12], data envelopment analysis [13,14] and equal weighting [15,16] to identify cross country patterns and potential catch-up mechanism for innovation activities.

Contributing to the two strands of the literature, the present analysis presents a composite RES innovation indicator for 26 European countries in 2010.[1] Methodologically, the assessment makes use of a factorial analysis, allowing the identification of the differences of innovation activities across the examined technologies: power generation technologies (wind and solar energy) are expected to depend significantly on the level of infrastructure that assures their integration into the electricity system, whereas transportation technologies are likely to be dependent on the evolution of the market. The novelty of the present work emerges both from the data collection and from the interpretation that was given to the constructed composite innovation indicator. A better understanding of the capabilities within the interdisciplinary knowledge systems is derived from the specific trade-offs between the individual indicators along a constant innovation capacity, which in turn should be able to inform the decision makers on the appropriate choice of research strategy. More specifically, the analysis seeks to identify complementarities among the technological capabilities, aiming to indicate potential synergies for the development of low carbon technologies. If different innovation patterns occur, specific policy measures should be designed, whereas certain technologies would respond better to technology push measures (research subsidies) rather than to market pull measures (such as feed in tariffs).

The structure of the paper is organized as follows. The second section presents the traditional background used for the present exploration. The third section presents data considerations. The fourth section presents the methodology used, describes the performance of the innovation indicator by the specific energy technology and identifies the associations between the technological capabilities for renewable innovation systems. The fifth section discusses the findings, and the sixth section provides the conclusions.

## 2. Background: policy learning through the mapping of the technological capabilities

Technological capabilities of nations have been previously taken into account through the main dimensions, such as the technological development, human skills and infrastructures [17,18]. Enablers of RES innovative activities comprise specialized financial and human resources, which, complemented by public support of research, development and demonstrations, are able to induce innovation activities. However, the impact of economic regulations on innovation is mixed [19], whereas public policies have been proven to be an important source for innovation, although such policies can also be an obstacle for innovation activities [20]. According to the latter studies, the intensity of product market regulations is negatively correlated with the intensity of research and development expenditure [21]. In the case of low carbon technologies, when examining the public support for deployment of the technologies, public efforts for research and deployment are effective in inducing innovation in more mature RES technologies [9,22], but negatively affect non-incremental innovation [23]. To learn from this mixed evidence, the best national energy research strategies should be mapped, and benchmarking should allow an effective examination of policy-induced innovation activities.

A complex environment is summarized by the use of composite indicators [4] that allow dealing with correlations among the various dimensions. For example, the variables describing the public support for the deployment and development of energy technology innovation are highly correlated, whereas most of the public policies are introduced simultaneously and used in tandem [9]. Furthermore, the structure of composite indicators enables sketching of the complementariness of various sources of innovation. For example, across a constant indicator, the patents are mirrored with the allocation of the resources for research [3], whereas the infrastructures are matched with sufficiently qualified labor [24,25]. These two dimensions are further examined, whereas the analysis highlights quantifiable capabilities at work, which are measured in terms of the effectiveness of RES deployment policies (jobs/MW) and as the effectiveness of RES public funding (leverage ratios). The intention of this paper does not seek to compare the economic efficiency of generation technologies, but is based on the employment and research ratios that designate which association of capabilities could be more efficient in increasing national innovation performance within the examined technologies.

The effectiveness of a specific regulation referring to the deployment was measured through the capacity of the green economy in creating jobs through an input–output analysis or using analytic surveys [26]. The employment generated by environmental policies, as measured through job ratios exhibits significant differences, depending on the intensity in RES deployment across countries [27], the specific factor capacity plants [26] or on the stage of participation in the supply chain [28]. Accordingly, specialized countries in technology manufacturing (*e.g.*, Denmark) register a low local deployment that falsely inflates the job per MW ratio. The number of jobs generated by installed capacities is likely to describe the opportunity cost of adopting market pull measures across countries.

Furthermore, the opportunity cost of adopting technology push measures could be traced through the trade-offs between the amount of private research expenditures and the number of patents. This association, previously described [3] through shadow prices [29], accounts for the compensating variation induced into one indicator (*i.e.*, patents) when another indicator (*i.e.*, research expenditures or researchers) varies. For example, Grupp and Schubbert [3] found a 1.05 shadow price between the academic population and the funds from enterprises to universities, whereas the indicator was 1.2 between 3rd degree education people and one (US) patent per one million inhabitants to keep the composite indicator unchanged. Through reasonable associations that are created, the composite indicator for RES technologies would be able to inform the position of various European countries and inform weakness within national technological capabilities. Furthermore, the changes within the indicator could indicate the direction of future public support, which

[1] 2010 was the most complete available year.

could opt either for their individual development or to an increase of synergies among diverse capacities.

## 3. Data considerations for composite innovation indicators

Due to data availability, the present analysis focuses upon RES innovation enablers for only 26 European countries[2] and for 2010, the most complete available year. The variables feeding the composite index are reminiscent of a production function, where *knowledge development* is enabled by generating inputs, such as *employment and infrastructure,* and *specific public support,* such as environmental policies (Table 1).

**Table 1**
Innovation output and enablers of innovation activities for energy technologies across EU-27 in 2010.

| Dimension | Indicator | Source | Solar energy | Wind energy | Bioenergy (Biodiesel/ Bioethanol) |
|---|---|---|---|---|---|
| **Knowledge development** | Number of patent application of national applicants to the National patent offices | Patstat, October edition 2011[a] | 513 | 819 | 213 |
| | Corporate R&D investment by energy technology | Own calculations[b], R&D total budget data obtained from annual reports, millions of euro | 435 | 647 | 734 |
| | National RD&D investments by energy technology | IEA RD&D statistics[c] million euro | 270 | 189 | 350 |
| **Knowledge development related to the infrastructure** | National RD&D investments in electricity grids | IEA RD&D statistics[c] million euro | 140 | | n.a. |
| | Corporate R&D investment in electricity grids | Own calculations[d], R&D total budget data obtained from annual reports, millions of euro | 95 | | n.a |
| **Infrastructure** | Market capacity in 2009: Installed MW - Solar, wind Thousand tonnes of oil equivalent-biofuels | World energy statistics 2013 | 16 371 | 74 951 | 9 104 |
| **Employment** | Employment in energy sector in 2009 | EURObserv'er, Geographic Information System[e] | 120 420 | 200 300 | 78 800 |

[a] The assessment does not account for the patent family.
[b] R&D calculated using WIPO patent share of technology investment in 2011, total R&D corporate budget in 2010.
[c] Consultation with Member States.
[d] R&D calculated using WIPO patent share of technology investment in 2011, total R&D corporate budget in 2010.
[e] http://observer.cartajour-online.com/Interface_Standard/cart@jour.phtml?NOM_PROJET=barosig&NOM_USER=&Langue=Langue2&Login=OK&Pass=OK.

The *knowledge development* of technologies is described through the use of patents and corporate research expenditures. In presenting these indicators at the national and sectorial level, the use of patent data provides a significant amount of informative power. First, the geo-location of patent applications enables the localization of the innovation activities and builds regional/ national innovation systems. Second, an aggregation of the relevant knowledge across several technological fields[3] enables the construction of a sectorial RES energy technology system. Third, and the most relevant for the present analysis, the distribution of patents allows the construction of private RES R&D investments, as there is a significant correlation between patents and R&D spending [30,31]. To this end, a sample of 60 European companies takes into account *pure wind* and *pure solar* companies, as well as large companies that are simultaneously active in many technologies, ranging from traditional fossil fuels to renewable energy sources (Appendix B). For the companies that are engaged in the development of more than one technology, the level of private R&D investment per specific technology is determined as a function of the company's shares of patent applications related to energy technologies to the total number of patent applications. The procedure follows several steps [32]: (1) the collection of total R&D investment data of these companies; (2) the allocation of the R&D investment to specific technologies (using the patent share determined above); (3) the summation of the R&D investment per technology from all identified companies; and (4) the aggregation at the national level. A time lag was also assumed to take into account the delay between the time that research occurs and its impact on innovation[4] [2]. The EU Industrial R&D Investment Scoreboard, annual reports and facts and figures of the European Patent Office and the WIPO (World Intellectual Property Organization) databases were jointly used to determine the research intensity of the European firms. The present patent based approach includes several limitations, among which: not all firms patent their activity because some opt for industrial secrecy to prevent knowledge spillovers [33,34], not all patents have important commercial use (Popp 2005, 2007) and the changes in environmental policy are difficult to be entirely captured through the direction of patenting activity. Despite these drawbacks, patenting is a systematic activity and is usually filed in the early stages of the technology life cycle [30].

*Employment and infrastructure.* Human skills participate in building up the national absorptive capacity [15], whereas cross-country differences in human capital explain the absorptive capacity. In cross-country regional studies, employment controls for the market size [35]. The spatial distribution of innovation activity for these technologies across EU countries is heavily influenced by the size of the market, in the sense that a larger market entails higher employment and thus, a larger basis for innovation activities. Furthermore, market size and market dynamics are able to stimulate the innovation activities of technology manufacturers and the regional distribution of their research and development investment. Proxied in our analysis by the installed capacities, European low-carbon energy deployment policies have been able to stimulate private research efforts.

Finally, the presence of *policy stimuli* for energy production is found to be a further driver of technological progress. Earlier research on environmental knowledge creation was conducted following the

[2] Austria, Belgium, Bulgaria, Cyprus, Checz Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Portugal Romania, Slovakia, Slovenia Spain, Sweden, and the United Kingdom.

[3] For example, solar energy is using knowledge coming from fields such as *Performing Operations*, *Fixed Construction* and *Electricity* (see Appendix A). (solar, wind and biofuels).

[4] Due to data availability, only one year lag is assumed between patents (2011) and R&D expenditures (2010). Large companies reveal their overall R&D budget, whereas small companies could opt not to disclose it. In order to deal with this limitation, for smaller companies, the average R&D investment per patent was considered the same as the one computed for large companies [2]. The R&D/patent intensity might change with future calculation.

Porter hypothesis [36], according to which strict environmental regulation can encourage innovation and efficiency [37,38]. The extent to which environmental policies are able to induce renewable energy innovation lies in their ability to increase the cost of using environmental resources. The rationale dates back to labor economics, where a relative increase in factor prices (the wage) was a spur to innovation directed towards economizing the resource that became more expensive (labor saving innovation). By the same token, an increase in the oil price or a tax on carbon should be able to affect the relative input prices and thus induce a $CO_2$ reduction innovation. Among the variety of instruments that have been used, non-reimbursable R&D and reimbursable public loans by complementing private underinvestment are able to stimulate the local research activities. Moreover, diffusion related policies, such as feed-in tariffs and tradable certificates are able to induce innovation in wind technology [9], as wind technology appears to be more mature and close to competing with fossil fuels than the other renewable sources, such as solar or ocean energy. Environmental support schemes therefore complement and reinforce private investment, acting as an important driver of renewable energy innovation. Public supports for research, hereafter called technology push policies, are synthetized in Table 1. The public R&D investment at the national level is provided by the IEA database on the Energy RD&D Budget/Expenditure Statistics, in which the missing data were completed using the "gap filling" method (JRC 2009, Wiesenthal 2011) that was subsequently validated through a distribution of questionnaires distributed to the Member States stakeholders [2]. The public RD&D data accounts for research, development and demonstration projects oriented towards the development of energy-related technologies, applied research, experimental development and demonstration.

## 4. Methodology and results

A generic vector of non-negative weights $w_i=[w1\ldots w7]$ is used to construct a composite index defined as the weighted average of the variables presented in Table 1:

$$\textit{Composite Innovation Indicator}_j = \sum_{i=1}^{I} w_i * y_{ij},$$

where $y_{ij}$ is the value of the indicator $i$ for the country $j$ and $w_i$ are the weights of the selected indicators. The choice of actual choice of weights is enabled by a principal component analysis, following several steps: (i) the variables presented in Table 1 are standardized to have a zero mean and one unit variance; (ii) the factors having the associated eigenvalues larger than one, contributing individually to the explanation of the overall variance by over 10% and contributing cumulatively to the explanation of the overall variance by over 85% (Appendix C); (iii) weights $w_i$ are calculated for the selected indicators[5] and (iv) according to the weights, the European countries are ranked based upon their localized capabilities.

Following the approach, it is found that in 2010, the innovation capabilities of wind and solar energy technologies depend to a large extent on the public support of research and development activities in wind and solar technologies (Appendix D), as well as on the subsidies seeking the development of the technologies allowing a higher integration in the market (RD&D programs for grid). Market subsidies, approximated by the level of installed capacity, had a smaller weight in building the innovation capacities for these technologies. Biofuel technology exhibited a higher contribution of the market (market capacity and human resources) and of the technology creation (the number of national patents). These weights were applied on selected individual indicators (Table 1) to build the performance of the innovation capacities of European countries.

The robustness of the ranking obtained using PCA has been confirmed in respect with those obtained using an equivalent weight method (EW): for the biofuels sectors, a small variation in the rankings between countries is observed, with the changes occurring within the same decile,[6] whereas for the wind energy and solar energy sector, a slightly higher variation of the ranking was observed between the methods for a group of 5 countries.[7]

In summary, except for a group of 8 countries, identified as sensible to changes in methods, but suffering only small shifting in ranking (and within same decile), the PCA and Equal Weighting seemingly provide a ranking of energy technology innovation across the European countries.

### 4.1. Landscape of energy technology innovation activities across the European countries

The highest performance of the innovation indicators in all the examined energy technologies is obtained for countries such as Germany, France, Italy and Spain. By technology, higher bioenergy innovation indicator values were registered for Poland, Sweden and the Netherlands, higher values of the wind innovation indicator are present in Denmark and the United Kingdom, whereas high values of the solar innovation indicator are present in Belgium and Austria. The sectorial values of the innovation indicator are significantly determined by research investments across different countries, which in their turn are driven by the commitment of the countries for the development of low carbon technologies. For example, Denmark, which in 2010 registered the highest level and intensity of research investment with a 0.19% of R&D to GDP ratio, reflects an important commitment to the development of wind energy technology (Table 2).

Most of the European countries, although revealing modest research intensity in relative terms (0.03% of GDP), present a more heterogeneous technology portfolio. A higher public biofuel-related R&D budget is present in France, Germany, Italy, and the UK, which also host specialized biofuel companies or large investors (car manufacturers and oil companies) with substantial research investments in biofuels (EUR 750 million). Germany is an important investor in solar energy technology, accounting for 61% of the total European R&D expenditure (EUR 901.03 million),[8] although other countries endowed with low solar irradiation conditions also have made significant private investments (Norway)[9] and public R&D investments (Netherlands). Wind energy R&D investments[10] are also highly concentrated, with a higher public support for research activities in the United Kingdom (EUR 67.33 million), Germany (EUR

[5] To minimize the number of individual indicators that have a high loading on the same factor, the coordinates used in PCA are changed (varimax rotation) so as to maximize the sum of the variances of the squared loadings (Appendix D). Finally, weights are obtained from the matrix of factor loadings after rotation (Appendix D), given that the square of factor loadings represents the proportion of the total unit variance of the indicators that is explained by the factor (Nicoletti et al., 2000; Nardo, 2008).

[6] Within the 7th decile, Belgium and the Czech Republic change places, and within the 3rd decile, Austria and Bulgaria change places.

[7] Among these countries, a higher variation is noted for Portugal, which switches place and shifts from the 6th to the 5th decile; lower variation is noted for Austria and Belgium, which are switching places within the 6th percentile. For the PV sector, a variation was observed between the two methodologies for countries such as Poland, Romania and Slovakia, which switch places within the 5th percentile. A higher variation for the PV sector is observed with respect to countries such as Poland and Demark switching places from the 4th to the 6th decile.

[8] The amounts refer to PV and CSP R&D investment. PV R&D investment amounts to EUR 0.81 billion, from which EUR 210.96 million are from EU Member states and EUR 28.93 million are from an FP7 contribution.

[9] From companies such as REC and Orkla Elkem solar.

[10] The corporate R&D investment amounts to EUR 670 million in 2010 estimates, which are consistent to the 2012 edition of BNEF, according to which global investment in wind technology development was USD 800 million.

**Table 2**
National research development and demonstration (RD&D) investments in the wind, solar, grid and bio-energy technologies.

| Country | Public RD&D investment (€billion) | Public and corporate research investment (€billion) | GDP (€ billion) | R&D investment/GDP (%) |
|---|---|---|---|---|
| **France** | 0.10 | 0.48 | 1937 | 0.02 |
| **Germany** | 0.12 | 0.86 | 2496 | 0.03 |
| **Denmark** | 0.04 | 0.45 | 236 | 0.19 |
| **United Kingdom**[a] | 0.13 | 0.32 | 1710 | 0.02 |
| **Italy** | 0.06 | 0.19 | 1553 | 0.01 |
| **Spain**[a] | 0.07 | 0.17 | 1049 | 0.02 |
| **Poland**[a] | 0.05 | 0.10 | 355 | 0.03 |
| **Netherlands** | 0.06 | 0.07 | 589 | 0.01 |
| **Sweden**[a] | 0.06 | 0.07 | 350 | 0.02 |
| **Finland** | **0.04** | **0.05** | **179** | **0.03** |

[a] The RD&D investment data for these countries are based on the content of IEA RD&D statistics database after being corrected by JRC-SETIS in consultation with the Member States. GDP data source: Eurostat for 2010 (online data codes nama_gdp_c and tec00001).

36.77 million) and Spain (EUR 23.76 million) and higher corporate investments in Denmark (EUR 361 million).

The geographic distribution of the wind, solar and bioenergy innovation indicators across Europe partially reflects the public commitment of these countries to integrate these technologies into their energy mix. In addition, a certain specialization in energy technologies could be depicted, whereas as a correlation analysis indicates that countries that invest in wind energy technology have a low share in nuclear RD&D investment and *vice versa* (correlation coefficient is nearly 0) (Fig. 1).

Not surprisingly, deployment of the RES technologies is the highly consistent spatial variability of wind/solar resources[11]: in 2010, well-endowed countries in wind and solar resources, the United Kingdom, Germany and Spain, accounted for 66% of wind cumulative installed capacities; in 2009, Germany alone accounted for 61% of European PV installed capacities. The presence of a large labor pool exerts an important contribution to the innovation indicator for countries such as Italy, Spain and Belgium.

A scarce diffusion of these energy technologies was observed for countries less well-endowed with solar and wind resources (Centre and Eastern Europe),[12] which accounted for 1.5% in the EU wind cumulative installed capacities and 2.8% of the PV cumulative installed capacities. Furthermore, an inverse association of energy resources was observed, with a low value of correlation between the percentage of electricity production from nuclear and installed capacities (0.08 for wind energy and 0.14 for PV). The same pattern was observed with respect to hydro resources, indicating a low correlation between the percentage of electricity production from hydropower and the installed capacities (−0.12 for wind and −0.13 for PV). These findings indicate an alternative explanation for the limited RES diffusion in those countries that lies in the substitute factor inputs [10]: countries that are endowed with hydro and nuclear resources have less motivation to invest into the renewable energy sector.

### *4.2. Synergies and associations between the technological capabilities for renewable energies*

Increasing synergies among the technological capabilities of the RES innovation system can be realized through an understanding of their compensating variation along a constant innovation capacity. In relation with the variables approximating the technology push or market pull support, these associations should be able to inform the decision makers on the appropriate choice of the research strategy. With respect to the deployment policies, insights can be found within the capacity of these sectors in creating jobs. Keeping constant the innovative composite indicator, the compensation variation for the loss of one job in the wind sector across the European countries indicates a 1.2 job/MW ratio, whereas the PV job ratio is 0.62 job/MW and 0.58 job/toe in the case of biofuels. For the case of power generating technologies (wind and solar), the present findings reflect the productivity of European and American employees. The number of jobs generated by wind energy was previously examined in the US [26,39] considering a European technology (manufacturer Vestas, Denmark). Accordingly, a 25-year lifetime for an onshore wind plant with a 35% capacity factor [39] and 228-MW peak capacity is able to generate 1.25 jobs per average MW (in the development and installation phase) and 0.4 jobs for operation and maintenance (*i.e.*, an average job ratio of 0.8/MW). Across countries, the direct employment in wind technology is variable [27], being higher for Belgium (6.97) and Denmark (5.44) and lower for Austria (0.76), Czech Republic (0.86), Spain (1.35), Germany (1.71) and France (2.44). These findings indicate mixed evidence with respect to the capacity of the green economy to create jobs. Comparing the economic efficiency of power generation technologies, Huntington [40] indicated a higher number of direct jobs created for PV technology and a lower number for wind and biomass. These results should be carefully taken into consideration, as biases might emerge from the participation of the countries in the supply chain. For example, countries specialized in the technology-manufacturing sector (high jobs rate) with most of the components exported (low local deployment), such as Denmark, might reflect a falsely inflated job per MW ratio [28]. Sastresa et al. [41] distinguished between operation/maintenance jobs and permanent jobs in the province of Aragon (Spain) estimated the job ratios that vary notably between renewable technologies; however, consistent with Wei et al. [28] 0.86 jobs/MW were created by the deployment of wind energy.

With respect to technology pull measures, the compensating variation (shadow prices) can be examined between output and input research indicators. Such examination indicates that a decrease of one wind patent national application would incur additional corporate R&D expenditures of 0.61 million euro to keep the value of the composite indicator unchanged. Previously, wind and solar R&D investment per patent has been estimated [42] to the amount of 1 million per wind/PV patents. The arbitrage between R&D investment and PV patents imply additional corporate R&D expenditures of 1 million euro to compensate a decrease by 1 of PV patent national application to keep the value of the composite indicator unchanged. Finally, the arbitrage between R&D investment and bioethanol patents imply additional corporate R&D expenditures of 0.9 million euros to compensate a decrease by 1 of bioethanol patent national application to keep the value of the composite indicator unchanged.

The joint examination of the jobs generated by the installed capacities with research trade-offs (research investment/patent,

[11] Countries in the West and North of Europe exhibit higher speed wind intensity than the Southern (Italy) and Central Eastern Europe (Czech Republic).

[12] Accounting for the countries that joined the European Union after the 2004 accession and the 2007 accession.

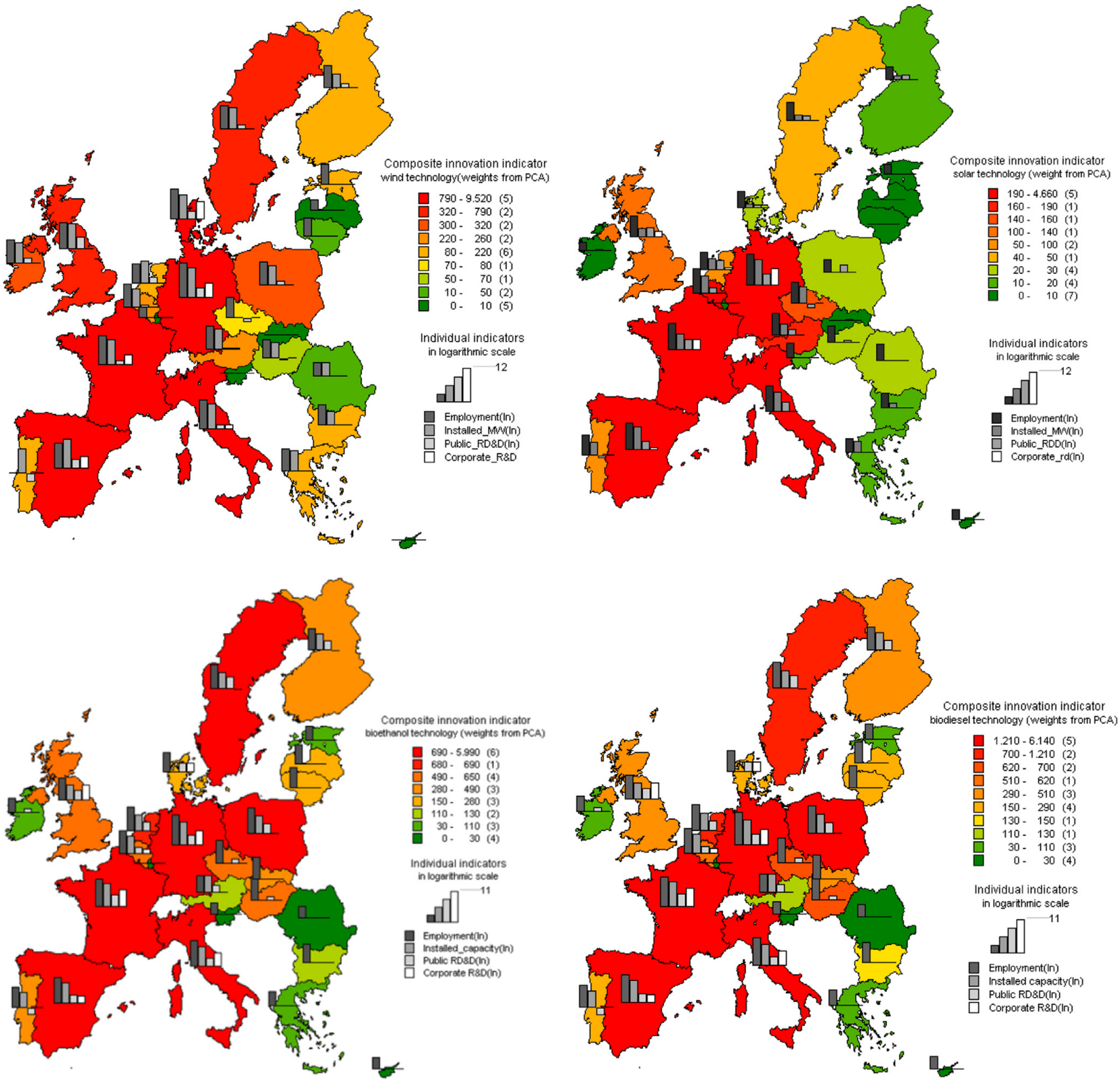



**Fig. 1.** Distribution of innovation capabilities for wind, solar and bioenergy technologies across Europe in 2010. The intensity of colors reflects the innovation indicator. The bars reflect the level of key individual indicators public and corporate RD&D, employment in the bioenergy sector and installed capacities in the bioenergy sector expressed logarithmic scale for graphical representation reason. (a) Distribution of innovation capabilities for wind technology across Europe in 2010. (b) Distribution of innovation capabilities for solar technology across Europe in 2010. (c) Distribution of innovation capabilities for bioethanol technology across Europe in 2010. (d) Distribution of innovation capabilities for biodiesel technology across Europe in 2010.

research in infrastructure/deployed capacity) are likely to describe the opportunity cost of adopting market-pull/technology-push measures across countries. For the present case, while manipulating the innovation indicator, it seems the consequences are higher if the deployment measures rather than research fundings suffer variations. This result highlights the dependence on the market mechanism of mature technologies.

## 5. Discussion of the results

The growth of the green sector relies on the health of multinational companies [43]. The examined technologies rely extensively on corporate efforts for technology developments, which account for 65% of European research investments. A joint examination of the associations between technological capabilities at the corporate level combined with the ongoing corporation industrial strategies might provide useful insights of the consequences of intense globalization occurring within these sectors.

In 2007, Europe was a global leader in wind energy technology, holding a 61% share of the globally installed wind energy capacity in 2007 and hosting 7 of the top 10 wind energy suppliers in 2006 (EUROBSERV'ER, 2008a, [44]). In 2010, Europe accounted only for 48% of total installed wind capacity and 27% of the newly installed capacity; and hosted only 5 of the top 10 wind energy companies. The penetration into new markets (especially in developing economies) triggered a reorganization of the production of wind manufacturers that go through closing production facilities in

Europe accompanied by the opening of research centers abroad (mainly Asia, the US). The effect of the restructuration for the wind energy technology has important consequences on the composite innovation indicator. For example, one million reductions in corporate R&D expenditures in Denmark reduces by 0.005% the innovation indicator, whereas one million reductions of public R&D expenditures reduces by 0.02% the innovation indicator. A reduction of 1000 employees in the wind sector decreases by 4% the indicator. The magnitude of this variation indicates a dependence of this technology on the market mechanism. Moreover, the effect of the delocalization could be estimated in the case of countries using an incentivizing tariff for wind energy deployment. For example, in Germany the monetary consequences of this reduction (expressed in terms of feed in tariffs) would range between EUR 93.5 and 171.456[13] paid to energy prosumers installing technology of non-European firms.

Significant consequences could also be noted with respect to solar technology. The European solar R&D investments in 2010 focused on the improvement of production processes and cost reduction for first and second PV generation (crystalline technology and thin-film), indicating a fast development publicly encouraged across the EU (and in particular in Germany). Such public interventions are manifested through the introduction of subsidies for the deployment of production and demand pull measures, such as feed-in tariffs (FiT), seeking to enhance learning effects for these technologies. As much as these measures have been successful for the diffusion of these technologies, the use of a FiT is prone to create surprising effects: the high price elasticity has stimulated domestic demand within Europe, but has also attracted foreign companies. Finally, such price elasticity has also redirected PV investments away from Europe (Germany) to emerging markets, such as China or India. The closure of European facilities has important consequences on the PV market: the reduction of 1000 employees in European facilities is reflected[14] in monetary terms (Feed in tariffs) of EUR 189.165 to EUR 252 million[15] redirected to energy prosumers importing the technology. The closure of European facilities could further manifest significant consequences on the innovation capacities of these countries.

In addition, the innovation capabilities for bioethanol technology were found to be highly elastic to market changes, reflected in substantial variations across countries: while maintaining constant the innovation indicator, the reduction by 1000 employees in the bioenergy has a substantial effect in Germany (a variation of 67% of the German capacity), whereas it has a much higher effect in Poland (a 4 times variation of capacities). Moreover, the reduction of 1000 employees in the bioethanol sector in 1733.867[16] (for biodiesel 1826.442) thousand tons *of oil equivalent* to keep constant the innovative composite indicator. The resultant of job reduction in monetary terms (*i.e*., feed-in tariffs paid to companies outside Europe) would result EUR 153.85–230.686 million (EUR 162–243 million for biodiesel) redirected to energy prosumers importing the technology. The amplitude of the changes reflects the support for biofuels within the European Union (EU), with the support often justified within job creation and economic growth[17] [45].

In summary, significant potentialities for the innovation activities in wind, solar and bioenergy technologies reside in the market evolution and the innovation capacities of the large firms. With respect to transportation technologies (biofuel technologies), the above results indicate a high sensitivity to market changes related to delocalization of corporations. Power generation technologies depend both on market evolution as well as on the evolution of the infrastructure. For example, variations in research electricity grids induce important adjustments upon research investments in wind technology: a variation of 1 MW of installed capacities for wind (solar) technology requires an additional EUR 1.335 million (EUR 2.058 million) of public R&D investments in the electricity grids to keep the wind (solar) innovation composite indicator unchanged. Consequently, high constraints are identified with respect to the level of public investments in the electricity grids for the innovation capacity of solar and wind technology. However, an increased participation of corporations to investments in the electricity grids could increase the performance of the innovation indicator.

## 6. Conclusion

The 2010 state of innovation in the selected low carbon energy technologies (wind, solar, and bioenergy) is herein described by the level of public and private investments in energy RD&D and by the intensity of public support for the deployment of these technologies, as measured through the installed capacities. The goal of the present study was to determine the relative importance of each of these determinants in building the overall performance of innovation activities for the three energy technologies considered. The final aim was to rank the European countries subject to the selected drivers and to identify the limitations or potential levers of innovation capabilities across Europe.

The study found that both public and corporate RD&D investments were commensurate to the size of the market: large countries, such as France, the United Kingdom, Germany, and Italy have higher research intensities in these technologies than the other European countries. Most of countries' industrial specialization reflects a multi-technological investment environment: Germany invests mostly in solar and wind energy, whereas in France, priority is given to bioenergy. Lower diffusion and research investment and outputs (patents) for these technologies was observed in the Eastern European countries, with inertia potentially reflecting previous investment choices in substitutable input technologies. EU countries share one or more priorities in public RD&D spending on energy technologies, which indicate that Europe has great potential in this front if more active policy coordination and synergies are exploited.

Moreover, the results of the study contribute to a better understanding of the capabilities within renewable energy knowledge systems, which is derived from the specific trade-offs between the individual indicators along a constant innovation capacity, and finally is able to inform the decision makers on the appropriate choice of research strategy. With respect to technology development, the present assessment identifies a higher R&D intensity for solar and biofuel technology than for the wind technology: briefly, the average corporate R&D intensity per patent is lower for wind EUR 0.61 million and higher for PV and biofuel (approximately EUR 1 million). Technology deployment is sensitive to the policy support, and in the present assessment we

[13] 1000 employees reduction is reflected within 1600 MW of installed capacities. The plants are assumed to be operational for 12 h per day and the onshore wind feed in tariff ranges between 4.87 and 8.93 cents/kW h according to http://www.germanenergyblog.de/?page_id=8617.

[14] 1000 employees reduction is reflected in 860 MW to keep the indicator unchanged. The plants are assumed to be operational for 12 h per day and the onshore wind feed-in tariff ranges between 18.33 and 24.43 cents/kW h according to http://www.germanenergyblog.de/?page_id=8617.

[15] http://www.germanenergyblog.de/?page_id=8617.

[16] 1 Toe =41.87 GJ=11.63 MW h, feed-in tariffs for electricity from biomass under the Renewable Energy Sources Act (EEG) 2009 in euro cents/kW h, with an annual reduction of 1% on basic tariffs and bonuses ranging from 7.63 to 11.44.

[17] Feed-in tariffs for electricity from biomass under Renewable Energy Sources Act (EEG) 2009.

identified job ratios similar to those described within the existent literature. Furthermore, we found that the adaption of companies to new markets entails important consequences on the overall innovation performance, and when comparing the overall effect on the innovation indicator, higher consequences were obtained when they were induced by the market.

Thus, high potential for innovation capacities was identified in the level of corporate R&D investments, which in 2010 represented over 65% of the total investments. Moreover, corporate participation in the investments in the electricity grids could reinforce the innovation capacities for power generation technologies. An intensification of the synergies for research in electricity grids support might increase the current allocation of resources and enable a spread of public investment thinly across several frontier technology research fields.

## 7. Appendix A

See Table A1.

## 8. Appendix B

See Table B1.

## 9. Appendix C

See Tables C1 and C2.

## 10. Appendix D

See Table D1.

**Table A1**
Classification of wind, solar and bioenergy patents according to International patent classification.

| Description | IPC codes |
|---|---|
| **Wind energy technology** | |
| Wind motors with rotation axis substantially in wind direction | F03D 1/00-06 |
| Wind motors with rotation axis substantially at right angle to wind direction | F03D 3/00-06 |
| Other wind motors | F03D 5/00-06 |
| Controlling wind motors | F03D 7/00-06 |
| Adaptations of wind motors for special use; | F03D 9/00-02 |
| Details, component parts, or accessories | F03D 11/00-04 |
| Electric propulsion with power supply from force of nature, *e.g.* sun, wind | B60L 8/00 |
| Effecting propulsion by wind motors driving water-engaging propulsive elements | B63H 13/00 |
| **Solar energy technology** | |
| Devices for producing mechanical power from solar energy | F03G 6/00-08 |
| Use of solar heat, *e.g.* solar heat collectors | F24J 2/00-54 |
| Machine plant or systems using particular sources of energy - sun | F25B 27/00B |
| Drying solid materials or objects by processes involving the application of heat by radiation | F26B 3/28 |
| Semiconductor devices sensitive to infra-red radiation - including a panel or array of Pv cells | H01L 31/042 |
| Generators in which light radiation is directly converted into electrical energy | H02N 6/00 |
| Aspects of roofing for the collection of energy—*i.e.* solar panels | E04D 13/18 |
| Electric propulsion with power supply from force of nature, *e.g.* sun, wind | B60L 8/00 |
| **Biodiesel, bioethanol energy technology** | |
| Preparation of carboxylic acid esters | C07C 67/00, 69/00 |
| Preparation of carboxylic acid esters | |
| Cracking hydrocarbon oils; production of liquid hydrocarbon mixtures, *e.g.* by destructive hydrogenation, oligomerisation, polymerization (cracking to hydrogen or synthesis gas c01b; cracking or pyrolysis of hydrocarbon gases to individual hydrocarbons or mixtures thereof of definite or specified constitution c07c; cracking to cokes c10b); recovery of hydrocarbon oils from oil-shale, oil-sand, or gases; refining mixtures mainly consisting of hydrocarbons; reforming of naphtha; mineral waxes | C10G |
| Liquid carbonaceous fuels, essentially based on components consisting of carbon, hydrogen, and oxygen only · Esters , containing hydroxy groups; Salts thereof Fats, oils, or fatty acids by chemical modification of fats, oils, or fatty acids obtained therefrom (sulfonated fats or oils C07C 309/62; vulcanized oils, *e.g.*) | C10L 1/02, 1/19 1/182 |
| Fats; Fatty oils; Ester-type waxes; Higher fatty acids, *i.e.* having at least seven carbon atoms in an unbroken chain bound to a carboxyl group; Oxidized oils or fats [3] | C11C 3/10 |
| Enzymes, *e.g.* ligases (6.); Proenzymes; Compositions thereof (preparations containing enzymes for cleaning teeth A61K 8/66, A61Q 11/00; medicinal preparations containing enzymes or proenzymes A61 K 38/43; enzyme containing detergent compositions C11D); | C12P 7/64 |
| Processes for preparing, activating, inhibiting, separating, purifying enzymes acting on glycosyl compounds | C12N 9/24 |
| Preparation of oxygen-containing organic compounds . Ethanol, *i.e.* non-beverage | C12P 7/06-7/14 |

**Table B1**
List of firms by technology.

| Technology | Selected companies |
|---|---|
| **Solar energy** | Centrotherm PV(DE), Conergy (DE), Manz automation (DE), Meyer Burger (CH), Oerlikon Solar (CH), PV Crystalox Solar (DE), PVA TePla (DE), Q-Cells ag (DE), Roth&Rau (DE) , Schott ag (DE), SMA Solar Technology (DE), Solar World (DE), Solon1 (DE), Sunways (DE), von Ardenne (DE), Wacker BU Polysilicon (DE). |
| **Wind energy** | Nordex (DE), Vergnet (FR), Siemens (DE), Vestas Wind (DK), Acciona Energy(ES), Alstom (FR), Gamesa (ES), Enercon (DE), REPower Systems (DE), Areva(Fr) Iberdrola (ES). |
| **Bioenergy** | (1) Novozymes (DK), Cursor Oy (FI), Air Liquide (FR), Arkema (FR), IFP Energies Nouvelles (FR), Marliere Philipe Instituts Pasteur (FR), Saint Gobain (FR), Tereos (FR), Total S.A. (FR), Veolia (FR), Diester Industrie (FR), Anaergia Inc (DE), BASF (DE), Bayer (DE), Bosch GmbH Robert (DE), Hoermann Interstall GmbH & Co KG (DE), KSB Aktiengesellschaft (DE), KWK GBR (DE), Linde (DE), Sattler AG (DE), Siemens (DE), Voith Patent GmbH (DE), ADM Biodiesel (DE), Crop Energies (DE), Eni (IT), Abengoa (ES), Biosling Ab (SE), Novartis (CH), BP(UK), Shell (UK). |

**Table C1**
Eigenvalues by technology.

| Component | Eigenvalue | Difference | Proportion | Cumulative |
|---|---|---|---|---|
| **Solar energy technology** | | | | |
| **Comp1** | 5.27 | 4.15 | 0.75 | 0.757 |
| **Comp2** | 1.12 | 0.77 | 0.16 | 0.91 |
| **Comp3** | 0.35 | 0.21 | 0.05 | 0.96 |
| **Comp4** | 0.13 | 0.04 | 0.02 | 0.98 |
| **Comp5** | 0.09 | 0.08 | 0.01 | 0.99 |
| **Comp6** | 0.01 | 0.01 | 0.00 | 0.99 |
| **Comp7** | 0 | | 0.00 | 1 |
| **Wind energy technology** | | | | |
| **Comp1** | 4.47 | 3.43 | 0.63 | 0.64 |
| **Comp2** | 1.04 | 0.35 | 0.14 | 0.78 |
| **Comp3** | 0.68 | 0.11 | 0.09 | 0.88 |
| **Comp4** | 0.56 | 0.37 | 0.08 | 0.96 |
| **Comp5** | 0.19 | 0.15 | 0.02 | 0.99 |
| **Comp6** | 0.03 | 0.02 | 0.01 | 0.99 |
| **Comp7** | 0.01 | . | 0.00 | 1 |
| **Biodiesel technology** | | | | |
| **Comp1** | 3.67 | 2.98 | 0.73 | 0.73 |
| **Comp2** | 0.68 | 0.30 | 0.13 | 0.87 |
| **Comp3** | 0.38 | 0.17 | 0.07 | 0.94 |
| **Comp4** | 0.21 | 0.16 | 0.04 | 0.99 |
| **Comp5** | 0.04 | . | 0.01 | 1 |
| **Bioethanol technology** | | | | |
| **Comp1** | 3.69 | 2.93 | 0.73 | 0.74 |
| **Comp2** | 0.75 | 0.33 | 0.15 | 0.88 |
| **Comp3** | 0.41 | 0.31 | 0.08 | 0.97 |
| **Comp4** | 0.10 | 0.06 | 0.02 | 0.99 |
| **Comp5** | 0.04 | | 0.01 | 1 |

**Table C2**
Factor loadings of Innovation system based on principal components by technology.

| | **Factor loadings** | | | **Squared factor loading** | | |
|---|---|---|---|---|---|---|
| | Comp1 | Comp2 | Comp3 | Comp1 | Comp2 | Comp3 |
| **Solar energy** | | | | | | |
| **Solar energy technology** | | | | | | |
| **National knowledge creation-patents** | 0.46 | −0.03 | 0.03 | 0.21 | 0.00 | 0.00 |
| **RD&D solar programs** | −0.00 | 0.98 | 0.00 | 0.00 | 0.98 | 0.00 |
| **Corporate research, solar technology** | 0.47 | −0.01 | 0.01 | 0.22 | 0.00 | 0.00 |
| **RD&D electricity grids** | 0.00 | 0.00 | 0.99 | 0.00 | 0.00 | 1.00 |
| **Corporate research electricity grids** | 0.43 | 0.01 | −0.03 | 0.19 | 0.00 | 0.00 |
| **Employment in solar sector** | 0.41 | 0.13 | −0.03 | 0.17 | 0.02 | 0.00 |
| **Market capacity: Installed MW** | 0.45 | −0.02 | 0.02 | 0.21 | 0.00 | 0.00 |
| **Variance explained by factor** | 0.99 | 1.00 | 1.00 | | | |
| **Share of variance explained by factor** | 0.33 | 0.33 | 0.33 | | | |
| **Wind energy technology** | | | | | | |
| **National knowledge creation-patents** | 0.40 | 0.22 | −0.00 | 0.16 | 0.05 | 0.00 |
| **RD&D wind programs** | −0.02 | 0.80 | 0.04 | 0.00 | 0.64 | 0.00 |
| **Corporate research, wind technology** | 0.52 | −0.42 | 0.05 | 0.27 | 0.17 | 0.00 |
| **RD&D electricity grids** | 0.00 | 0.01 | 0.99 | 0.00 | 0.00 | 0.99 |
| **Corporate research electricity grids** | 0.50 | −0.01 | −0.05 | 0.26 | 0.00 | 0.00 |
| **Employment in wind sector** | 0.45 | 0.07 | 0.03 | 0.21 | 0.00 | 0.00 |
| **Market capacity: Installed MW** | 0.32 | 0.36 | −0.06 | 0.10 | 0.13 | 0.00 |
| **Variance explained by factor** | 0.99 | 1.00 | 0.99 | | | |
| **Share of variance explained by factor** | 0.33 | 0.33 | 0.33 | | | |
| **Biodiesel technology** | | | | | | |
| **Bioethanol** | | | | | | |
| **National knowledge creation-biodiesel patents** | 0.62 | −0.03 | 0.14 | 0.38 | 0.00 | 0.02 |
| **RD&D bioenergy programs** | −0.01 | 0.00 | 0.98 | 0.00 | 0.00 | 0.97 |
| **Corporate research, bioenergy technology** | 0.75 | −0.02 | −0.09 | 0.57 | 0.00 | 0.01 |
| **Employment in biodiesel sector** | −0.10 | 0.80 | 0.016 | 0.01 | 0.64 | 0.00 |
| **Market capacity** | 0.19 | 0.59 | −0.02 | 0.04 | 0.35 | 0.00 |
| **Variance explained by factor** | 1.00 | 0.99 | 1.00 | | | |
| **Share of variance explained by factor** | 0.33 | 0.33 | 0.33 | | | |
| **Bioethanol technology** | | | | | | |
| **Bioethanol** | | | | | | |
| **National knowledge creation-bioethanol patents** | 0.67 | −0.08 | 0.11 | 0.45 | 0.01 | 0.01 |

**Table C2** (*continued*)

| | Factor loadings | | | Squared factor loading | | |
|---|---|---|---|---|---|---|
| | Comp1 | Comp2 | Comp3 | Comp1 | Comp2 | Comp3 |
| **RD&D bioenergy programs** | −0.00 | 0.01 | 0.98 | 0.00 | 0.00 | 0.98 |
| **Corporate research bioenergy technology** | 0.71 | 0.03 | −0.09 | 0.50 | 0.00 | 0.01 |
| **Employment in biofuels sector** | −0.10 | 0.79 | 0.021 | 0.01 | 0.63 | 0.00 |
| **Market biofuel capacity** | 0.18 | 0.60 | −0.02 | 0.03 | 0.36 | 0.00 |
| **Variance explained by factor** | 1.00 | 1.00 | 1.00 | | | |
| **Share of variance explained factor** | 0.33 | 0.33 | 0.33 | | | |

**Table D1**
Weight of the components of a composite innovation indicator obtained from PCA for each energy technology across EU 27 in 2010.

| | Solar energy technology (%) | Wind energy technology (%) | Biodiesel technology (%) | Bioethanol technology (%) |
|---|---|---|---|---|
| **National patents** | 7.10 | 6.10 | 13.10 | 15.50 |
| **Research, development and demonstration programs for specific technology: solar, wind , biofuels** | 32.80 | 24.10 | 33.20 | 33.40 |
| **Research, development and demonstration programs in electricity grids** | 33.60 | 37.20 | | |
| **Corporate research** | 7.50 | 10.20 | 19.50 | 17.20 |
| **Corporate research in electricity grids** | 6.20 | 9.70 | | |
| **Employment by sector** | 5.80 | 7.80 | 22.10 | 21.50 |
| **Market capacity** | 6.80 | 4.80 | 12.20 | 12.40 |

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